Life Cycle Thinking

Designing the Ideal Green Product:

LCA/SCLA in Reverse

Thomas E. Graedel

Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974, USA

Present address: School of Forestry and Environmental Studies, Yale University, Sage Hall, 205 Prospect Street, New Haven, CT 06511, USA

Abstract

Traditional life-cycle assessment begins with a product and examines its environmental impacts throughout its life cycle. An alternative approach is to proceed in reverse: to examine the need that the product is designed to fulfill, to determine the minimal environmental impacts that could be engendered by filling that need, and thereby to design the "ideal green product" for the purpose. This approach, termed reverse life-cycle assessment (RLCA), is demonstrated by examining the environmental impacts attributable to a generic washing machine of current design, and then by reviewing other ways in which the provisioning of clean clothing may be accomplished. RLCA, as used here, is shown to encourage systems thinking and to identify opportunities for innovation in design and in marketing of environmentally-responsible products in ways that would be unlikely to arise from a traditional LCA.

Keywords: Environmentally responsible products; life cycle thinking; product design; reverse life-cycle assessment (RLCA); streamlined life-cycle assessment (SLCA)

1 Introduction

Industrial designers are increasingly attempting to describe and design the "green product", one that is environmentally responsible in its design, manufacture, use, and at end of life. Environmentally responsible design is a complex topic, however, and designers require formal analytic approaches to determine what is a green design, and how to make a given design greener. Life-cycle assessments (LCAs) [1], and their increasingly-used progeny, streamlined life-cycle assessments (SLCAs) [2], are the most common of the analytic approaches, and are undeniably useful. The results of LCAs and SLCAs are, however, not definitive, and are widely regarded as prone to producing contentious results [3, 4].

An alternative approach to developing a design and then assessing its environmental attributes is to broaden one's perspective and consider not the greenness of a particular design, or a particular product, but the fact that a product exists to fulfill a specific need or desire of society. One may then ask not whether a particular product is green, but rather what sort of product would be the ideal way to fill the need or desire that has been identified while minimizing unwanted environmental impacts. This needs-based approach can be studied, in principle, by performing the LCA or SLCA in reverse, that is, by beginning with the environmental characteristics of an ideal product and then working backwards to determine the physical design approach that would most nearly satisfy those characteristics.

The present paper demonstrates this new approach by analyzing a familiar consumer appliance: the generic washing machine, which performs 350–400 washes per year and has an average life of 10–14 years [5]. The characteristics of a present-day machine are first presented, and an SLCA analysis performed. The results exemplify the attributes, good and bad, of the modern approach to the provisioning of clean clothing. The SLCA is then performed in reverse: the need, rather than the product, is the starting point, and desirable attributes of a product meeting that need are identified. Alternative approaches to designing a product possessing those attributes are then evaluated.

2 Life Cycle Analysis of the Generic Washing Machine

2.1 The washing machine life cycle

It is useful to begin the assessment by reviewing the life cycle of the generic washing machine and the constituent parts and subassemblies from which it is made *(→ Fig. 1)*. The life cycle can be summarized in the following stages:

1. Fabrication of individual components and materials, including the frame, the mechanical components, the electrical and electronic components, and the housing. Much of this fabrication is done by suppliers.
2. System assembly, in which mechanical and electrical components are assembled into frames, system plumbing and wiring is added, and system tests are performed.
3. Product delivery, in which finished washing machines are packaged and shipped, sold, and installed on customer premises.
4. In-service use, in which the product performs the washing actions desired by the customer.

5. In-service maintenance, in which repairs and updates to the machine are performed in order to keep it in use.
6. Recycling and/or disposal, in which materials from obsolete products re-enter materials streams or are lost to the industrial process as a consequence of landfilling, incineration, or other disposal techniques.

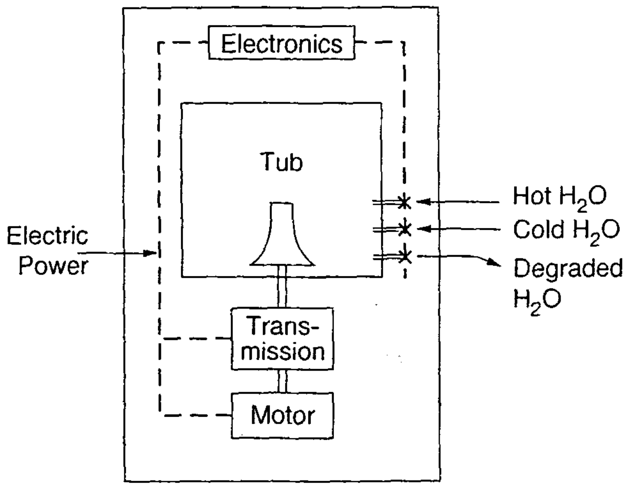

Fig. 1: Components of a generic washing machine

2.2 Assembly flow

The flow diagram for the washing machine life cycle is shown in **Figure** 2. The sequence proceeds from the top of the diagram to the bottom, while components and subassemblies enter from the left of the diagram. Waste products leave processing steps to the right. In general, incoming parts and components are packaged in a variety of plastic and cardboard containers, often with wood bases and metal strapping. It is rare for attempts to be made to achieve uniformity in supplier packaging, or to coordinate or optimize supplier deliveries so as to minimize their environmental impacts.

In the first assembly step, the electromechanical components of the system (motor, transmission, etc.) are affixed in the frame. These components are largely of steel and copper. Next, the mechanical components are added. These include the plumbing connections, largely of stainless steel and plastic, and the tub and other components of the washing compartment, most of which are plastic. The third step is the addition of the control panel and of the wiring that connects the panel to the electromechanical components. These items incorporate electronic circuit boards (and thus lead/tin solder, plastic, and metals in connectors and fasteners) as well as copper conductors and plastic cable sheathing. The next step is to affix the external housing panels: sides, top, front, and back. Most of these items are manufactured of enameled steel, both for corrosion resistance and to permit the product exterior to be made in different colors. In all four of these stages, the components that are added have arrived at the manufacturing facility in their own packaging; that packaging must either be dis-

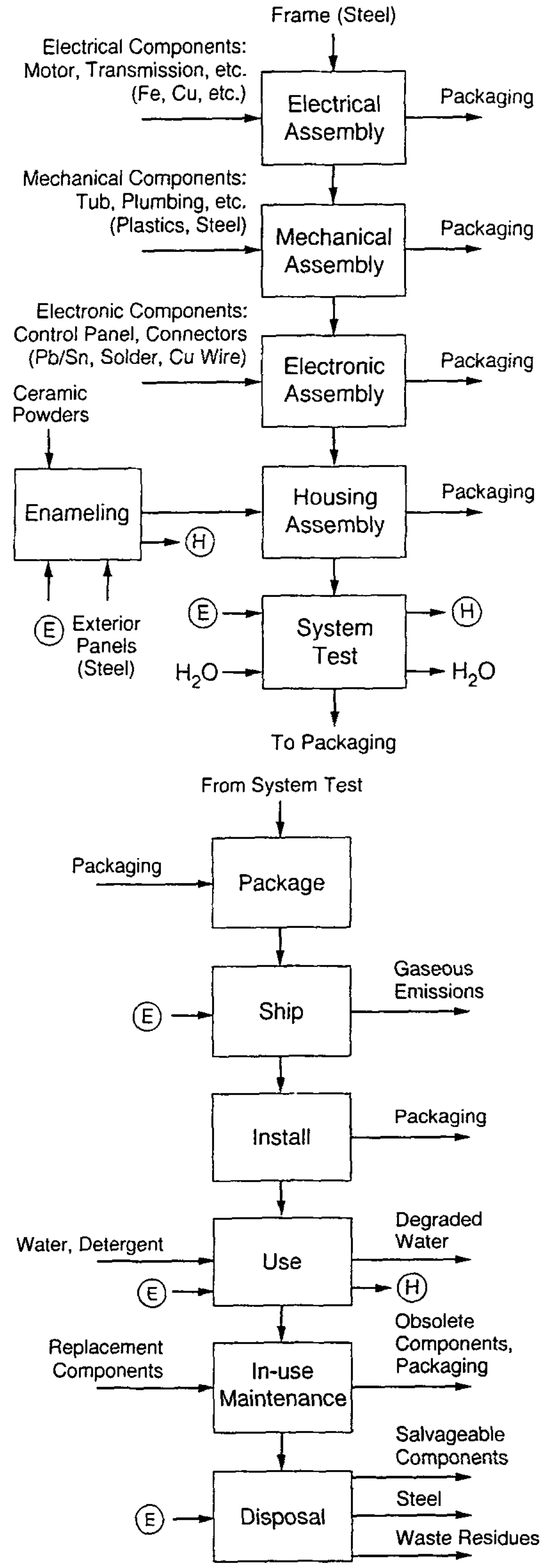

Fig. 2: A life cycle flow diagram for the generic washing machine, including manufacture, use, maintenance, and end of life. Rectangles indicate process flow steps; material or subassembly flows into the process enter from the left; material flows to waste disposal and recycling processes exit to the right. Significant energy use is indicated by a circled E, significant heat loss by a circled H

carded or otherwise dealt with. The final factory step is testing of the completed unit, an operation that involves the use of energy and water, but no new materials. After completion and testing, the washing machine is packaged for shipment to the customer. Typical packaging involves a wood or heavy corrugated cardboard base, some internal polymer cushioning, an external corrugated cardboard box, and steel strapping tape to retain the packaging. Shipment to the point of sale and ultimately to the customer then occurs, normally by truck. The unit is subsequently installed in the home, generally by an employee of the point of sale organization. Disposal or recycling of the packaging is usually left to the customer.

In use, the washing machine consumes energy, heated water, detergent, and perhaps other washing agents in producing clean clothing. During the useful life of the machine, components that become defective are repaired or replaced. Finally, the machine is disposed of, and a disposal or recycling system deals with the obsolete unit.

3 Streamlined LCA Analysis of the Generic Washing Machine

3.1 The matrix approach

The SLCA approach that is used here has as its central feature a 5x5 assessment matrix, one dimension of which is life-cycle stage and the other of which is environmental concern [6]. The life stages treated are premanufacture, manufacture, product delivery, product use, and refurbishment, recycling, and disposal; the environmental concerns addressed are the choice of materials, energy use, and solid, liquid, and gaseous residues [7]. In use, the assessor studies the product design and implementation and assigns to each element of the matrix an integer rating from 0 (highest impact, the most negative possible rating) to 4 (lowest impact, the most exemplary possible rating). In essence, what the assessor is doing is providing a figure of merit to represent the estimated result of the more formal LCA inventory analysis and impact analysis stages. She or he is guided in this task by experience, a design and manufacturing survey, appropriate checklists, and other information. The process described here is purposely qualitative and utilitarian. It can be appropriate to apply weighting factors to these assessments [8], but such an enhancement is not beneficial in the present work.

3.2 Premanufacture

The premanufacture assessment stage could, in principle, treat impacts on the environment as a consequence of the actions needed to extract materials from their natural reservoirs, transport them to processing facilities, purify or separate them by such operations as ore smelting and petroleum refining, utilize the materials in the manufacture of parts and components, and transport the products to the factory where they are incorporated in new washing machines. Such an analysis would include consideration of plastics formulations and treatment of associated industrial waste, air emissions from metal enameling processes, and the like. In practice, such an assessment tends to be impractical, and responsible manufacturers deal with "premanufacturing" issues by assuring themselves that their suppliers incorporate environmental responsibility into their own business operations. As a result, the premanufacturing assessment stage is restricted to evaluation of the impacts on the manufacturer's environmental performance that arise from the materials and design choices by suppliers and the packaging and transport of components to the manufacturing facility. Since a washing machine is primarily the result of an assembly of parts supplied by others, the final product's environmental responsibility is in large degree established by the choices made by supplier design engineers.

Component designers, in general, make good materials choices from a DFE standpoint. Few of the materials have any toxicity problems and those materials of some concern are present in small amounts or in situations where the hazardous aspects are minimized. The use of scarce resources is modest.

Notwithstanding the above, several materials choices should be noted as items to be improved if opportunities present themselves:

- Lead solder on circuit packs. The bioavailability of this lead is not great, and detailed investigations of alternative solders have not yet yielded a suitable replacement. Nonetheless, the toxicity of lead and its environmental persistence is such that its use anywhere is undesirable if alternatives can be developed.
- Metal frames, bolts, and screws use zinc chromate coating for corrosion resistance. The hexavalent chromium in zinc chromate is biotoxic and will eventually enter the soil or water waste flow streams, so the development of substitute corrosion coatings is desirable.

A frequent opportunity for improvement at the premanufacture stage is to specify the use of recycled material where possible in items or materials purchased from suppliers. Such an activity is essential for all designers if materials flows are to be sustainable in the long term. Among the possibilities worth considering here are recycled metals in equipment frames, recycled plastics as ingredients of plastic parts, and recycled material for boxes and other packaging items. In every case, of course, the recycled material would need to meet appropriate performance specifications and have less environmental burden than do the virgin materials it replaces.

These considerations lead to the following ratings for the premanufacture life stage, where the numbers in the left column are the matrix element designations:

Premanufacture	
Element Designation	Element Value and Explanation
Matls. choice (1,1)	1 (Use of lead and chromate)
Energy use (1,2)	2 (High energy use in deliveries)
Solid res. (1,3)	2 (Abundant and diverse packaging)
Liquid res. (1,4)	4 (No concerns)
Gas res. (1,5)	2 (Substantial air pollution from deliveries)

3.3 Product manufacture

Product manufacture is the life stage most likely to have been assessed for environmental impact by industrial engineers, since such aspects of it as emissions to air and water are subject to review by governmental authorities. Other characteristics of manufacture are not covered by such oversight, however, and all facets need to be part of a life-cycle assessment. In the manufacture of the generic washing machine, the most significant environmental impact is likely to be the enameling operation. In this process, ceramic and glass powders are applied to metal surfaces, which are then heated to some 800 degrees C to melt and fuse the powders to the metal. Large amounts of energy are used, substantial heat is lost, and organic and inorganic gases are produced and emitted. Little solid residue is produced in washing machine manufacture. Most electrical and fluid connections, for example, are supplied in the desired lengths, so no cutting scraps result. Liquid residues are minimal as well. All machines are tested when completed, with the water and detergent being recycled.

Product Manufacture	
Element Designation	Element Value
Matls. choice (2,1)	2 (Minor lead and powder toxicity concerns)
Energy use (2,2)	2 (Copious energy use during enameling)
Solid res. (2,3)	3 (Little solid residue produced)
Liquid res. (2,4)	3 (Minor liquid residues from testing)
Gas res. (2,5)	3 (Inorganic and organic emissions from enameling)

3.4 Product delivery

This life stage includes the environmental impacts arising from residues generated or energy used during the packaging process, transportation of the finished and packaged product to the customer, product installation, and disposal or recycling of the packaging material. The traditional task of the packaging engineer has been to devise packaging that safeguards the product between manufacture and installation. Minimizing cost has been a part of the considerations involved, but the environmental impacts of the packaging have traditionally not been considered. As a consequence, washing machine packaging typically contains a mixture of materials (cardboard, foam, plastic sheet, steel strapping, etc.) and its disposal is left to the customer. Information on proper recycling of the packaging material is seldom provided, so even someone with the intent to recycle does not know, for example, what polymer is used in making the plastic sheet that covers certain of the components to prevent scratches. Properly marking the packaging material obviously would not guarantee that it would be recycled, but would improve the possibilities.

Product Delivery	
Element Designation	Element Value and Explanation
Matls. choice (3,1)	1 (Substantial materials diversity in packaging)
Energy use (3,2)	2 (Energy use in delivery not optimized)
Solid res. (3,3)	1 (No plans for material recovery and recycling)
Liquid res. (3,4)	4 (No concerns)
Gas res. (3,5)	2 (Gaseous emissions in delivery not optimized)

3.5 Product use

This life stage includes impacts from consumables and maintenance materials that are expended during the period in which the washing machine is used by the customer. The typical washing machine has significant environmental impacts as a result of in-service operation. The most obvious, and one that deserves the most attention, is the energy required to heat the water, and for motor and valve operation. Water consumption and discharge are also major issues. The use of detergents and other washing products must be considered, as well as the environmental consequences of the maintenance and repair functions that are inevitably required.

Product Use	
Element Designation	Element Value and Explanation
Matls. choice (4,1)	4 (No concerns)
Energy use (4,2)	2 (Little energy minimization)
Solid res. (4,3)	2 (No plan for defective part reuse)
Liquid res (4,4)	2 (Water use, detergent discharge)
Gas res. (4,5)	4 (No concerns)

3.6 Refurbishment, recycling, disposal

The fifth life stage assessment includes impacts from product refurbishment and as a consequence of the eventual discarding of modules, components, or entire products deemed impossible or excessively costly to recycle. The typical washing machine contains materials such that perhaps 60 weight percent of a typical product is immediately reusable or recyclable with no design changes. Examples include the steel frames and the mechanical components. The recyclability of much of the system is a chance occurrence, however, because insufficient thought has customarily been given at any design stage to the eventual potential or efficiency of recycling. Examples of this understandable omission can readily be demonstrated:

- Nearly every subassembly, though not necessarily the side panels, is attached by using screws in threaded holes. This technique is time-consuming, both during assembly and disassembly. Other industries, particularly the automotive industry, have shown that a variety of new pop-in pop-out fasteners, quick-disconnect designs, and the like are quite secure and rigid, while being much more efficient in installation and disassembly.
- There is significant nonuniformity in the plastics used in the washing machine, an approach that makes recycling much more difficult. Thermosets and thermoplastics of different kinds appear in various components manufactured by various suppliers, with no overall attempt at minimization of plastics diversity or recycling efficiency. Regardless of the level of diversity, each plastic part should carry identification marking as designated by the International Standards Organization [9], but this is not common practice.
- Mixed materials often are joined in ways difficult or time-consuming to reverse on a recycling line. For example, enameled steel is a very difficult construction from which to recover constituent materials.
- No reuse plan is in place for electronic components

Refurbishment, Recycling, Disposal	
Element Designation	Element Value and Explanation
Matls. choice (5,1)	2 (Lead presents toxicity complications)
Energy use (5,2)	2 (No minimization of energy use at recycling)
Solid res. (5,3)	1 (High materials diversity, little modularity, no ISO markings)
Liquid res. (5,4)	4 (No concerns)
Gas res. (5,5)	3 (Some air pollution likely from metal recovery)

3.7 SLCA assessment results

For convenience in summarizing the environmentally-related characteristics of the generic washing machine, **Table 1** collects the matrix assessment values for each of the five life-cycle stages and for the unit as a whole. The ensemble score is produced by linear addition of the twenty-five matrix values; the result is 60 out of a possible 100 points. A comprehensive LCA would probably weight the product use phase heavily to reflect the long time span during which its environmental impacts occur, but the same deficiencies would likely be singled out for attention by either the LCA or SLCA approach.

Table 1: The environmentally responsible product matrix for the generic washing machine

	Environmental Concern					
Life Stage	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Row Total
Premanufacture	1	2	2	4	2	11/20
Product Manufacture	2	2	3	3	3	13/20
Product Delivery	1	2	1	4	2	10/20
Product Use	4	2	2	2	4	14/20
Refurbishment, Recycling, Disposal	2	2	1	4	3	12/20
Column Total	10/20	10/20	9/20	17/20	14/20	60/100

4 Needs-Based Approaches

The above assessment of the typical washing machine has identified many areas in which its environmental atttributes are less than ideal, chief among them being the use and discharge of energy, water, and detergents during use, the manufacture and subsequent need for recycling of packaging material by component suppliers and washing machine manufacturers, and the difficulties of materials recovery and recycling at end of product life. From the standpoint of the environment, the ideal product would have a matrix assessment rating as shown in **Table 2**: perfect scores for all matrix elements. Given the traditional approach to the provisioning of clean clothing exemplified by the washing machine, is it possible to anticipate that a set of perfect scores can ever be achieved by this approach, while simultaneously providing customer satisfaction?

Table 2: The environmentally responsible product matrix for the ideal green provisioning of clean clothing

	Environmental Concern					
Life Stage	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Row Total
Premanufacture	4	4	4	4	4	20/20
Product Manufacture	4	4	4	4	4	20/20
Product Delivery	4	4	4	4	4	20/20
Product Use	4	4	4	4	4	20/20
Refurbishment, Recycling, Disposal	4	4	4	4	4	20/20
Column Total	20/20	20/20	20/20	20/20	20/20	100/100

To begin with, it is unrealistic to imagine that any product can be manufactured while having absolutely no effect on the environment. The very nature of a product is that its manufacture involves the use of materials (thus involving resources) and generally their transport and transformation (thus involving energy). An ideal green product is therefore not one that has no environmental impact, but one that satisfies the customer need with the absolute minimum environmental impact. Given this perspective, consider the premanufacture life stage. Matrix element 1,1 could be given a perfect score should it be possible to eliminate all toxic materials in supplier products. Since at present there are available a variety of anticorrosion coatings and conductive adhesives, it is reasonable to anticipate eventual toxic material elimination. Similarly, we can anticipate the eventual recycling or elimination of supplier packaging (1,3), although the specific ways in which this may be accomplished are unclear, as is the development of delivery methods and transportation technologies that would greatly minimize transport-related impacts (1,2 and 1,5). Thus, in the premanufacture life stage, there are significant technical challenges but no intractable constraints that would ultimately prevent the washing machine from becoming an ideal "green product".

A similar conclusion is reached concerning the manufacturing life stage. The substitution for enamel of an alternative protective coating such as those used on automobile exteriors has the potential to essentially eliminate manufacturing energy losses (2,2), as well as atmospheric emissions (2,5) and related toxic concerns (2,1). Again, there appear to be no "show stoppers".

The product delivery stage is amenable to a number of fairly straightforward solutions to environmental concerns, at least in principle. One can imagine the elimination of packaging diversity (3,1), the recovery and reuse or the efficient recycling of packaging materials (3,3), and optimization of deliveries to point-of-sale and customer locations to reduce transport-related impacts to low levels (3,2 and 3,5). As before, these changes appear to be completely feasible.

At the customer use life stage, new approaches to defective parts provisioning (longer mean lifetimes, efficient reuse of returned components) can probably minimize solid waste concerns (4,3). However, so long as clothing is washed in

water and detergent and then dried, one can reduce but not eliminate the substantial use and depletion of energy and water (4,2 and 4,4) that is involved. These two requirements will forever make it difficult or impossible to design a "perfectly green" washing machine using traditional approaches.

Finally, look to the end of product life. The toxicity concerns (5,1) can be eliminated given good materials choices by suppliers, and thoughtful design for dissassembly is likely to minimize, but not eliminate solid residues (5,3) and to reduce emissions (5,5) and energy use (5,2) to negligible levels. Hence, the environmental impacts of life stage 5 are open to improvement, but perhaps not impact-free transformation.

The reverse life-cycle assessment has thus suggested that the traditional washing machine can eventually be greatly improved from an environmental standpoint, but that its environmental impacts can never be completely eliminated. This conclusion is reinforced when one takes account of the fact that most washing machines are used in conjunction with electric or gas dryers, and those appliances also utilize resources and produce waste products. A similar result has been derived by looking at the problem from another standpoint: that of the environmental impacts attributable to an article of clothing. In a study performed by Franklin Associates for the American Fiber Manufacturers Association [10], energy use for laundering a woman's polyester blouse was estimated at some four times that used in manufacturing the garment, and solid residues related to municipal sludge and ash from off-site energy production were largely attributable to the consumer life stage as well. Improvements suggested were the use of cold wash cycles and line drying, both of which seem likely to result in decreased customer satisfaction.

From this discussion, it is apparent that in the typical washing machine we have a product created in response to a perceived need: that of the provisioning of clean clothing with maximum convenience and at affordable cost. From earliest civilization this need has been recognized, and it has been met throughout human history in essentially the same way – by treating garments as precious items to be preserved and maintained, and by using water and detergents to preserve and maintain them (mending and other repairs excepted). This system, already effective, could certainly be improved while taking the same basic approach to the need. There is no obvious reason why the desire for clean clothing can only be satisfied in this way, however. A "brainstorming" approach to this need might imagine clothing that could be cleaned in other ways, as is the case currently for those fabrics that must be dry-cleaned professionally. Alternatively, one could imagine manufacturing recyclable clothing so efficiently and inexpensively that clothing might never need to be cleaned at all, but could be recycled after each wearing. Let us examine the attributes of each of these possible alternatives.

Option 1 is the *traditional approach*, in which clothing is washed periodically in (generally heated) water, detergents, and perhaps other laundry products. A warm air dryer is not required as an adjunct to the washing machine, but in practice, at least in North America and much of Northern Europe, a dryer is almost always present. The latter requires electricity to operate, and uses either electricity or natural gas to heat the air for drying.

Certain fabrics perform better than others under numerous cycles of wearing, washing, and drying, and fabric manufacturers have evolved their products to be compatible with traditional washers and dryers. For some fabrics, however, suitable home systems have never been developed, and professional dry cleaning is required. Thus, taken all in all, a washing machine can be pictured as a component in a system of clothing provisioning that includes fiber growing and petroleum recovery, clothing manufacture, transport, sale, customer use, repeated washing and drying (or repeated dry cleaning), and disposal. The *system* is what one wishes to optimize from an environmental standpoint, not just the *washing machine*.

The traditional clothing provisioning system has several advantages. The most obvious is that it is a system already in place. Consumers have purchased clothing and washers and dryers that together provide what they wish: good-looking, relatively long-lasting, easily-cleaned garments. For some fabrics, dry cleaning is needed and this infrastructure is in place as well. The disadvantages of the system are equally obvious: substantial use of energy and water occurs, chlorinated dry-cleaning solvents with potentially significant impacts on the workplace and the environment are emitted, and the technological approach is such that while these consequences may be mitigated, they can probably never be eliminated.

The **second option** is to retain the same basic approach we now take toward providing clean clothing, but to re-engineer that approach for optimum environmental performance. One can envision energy, water, and detergent use being markedly reduced. It may also be possible to optimize the rinse cycle and incorporate heat or radiation drying within the washer so as to eliminate the dryer altogether. This approach, following the "less is better" philosophy, would decrease, but not eliminate, the environmental effects of providing clean clothing.

Option 3 is a system in which clothing is cleaned without the use of water, but rather with some alternative technique such as infrared or microwave radiation. Liquid detergents might not be required; one could envision a system in which a detergent powder adhered to soil and served as a locator for the radiant energy, for example. Since no wetting of clothing would be involved, no drying would be required. Dry cleaning for some fabrics might or might not still be needed.

Option 3 has as its principal advantages the elimination of the use of water, much of the energy, and perhaps detergents characteristic of the present system. Its principal disadvantage, of course, is that it has not been developed. A likely possibility is that such a system might be realized but only for specialized fabrics, in which case the clothing industry and its suppliers would have to be collaborators in the development of a new integrated system. Were the system to be realized technically, it would also be necessary to deploy it at a reasonable cost. Additionally, perhaps the

most difficult requirement for any departure from common practice, it would have to be demonstrated that the new technique and the new clothing materials (if any) were at least as satisfactory to consumers as the old.

The **fourth option** that might be considered is the design and manufacture of "one-time" clothing, as we now do with other products such as adhesive bandages. The concept here is that clothing that met customer needs would be manufactured, delivered, and sold in an efficient manner, worn once, and then recovered much as newspapers are routinely collected today. The recovered clothing would be reprocessed into newly-manufactured "one-time" clothing.

As with Option 3, the advantages of Option 4 are the elimination of energy and water use during washing and drying. The disadvantages are, first, that the Option 4 system has not been realized technically, and second, were it to be realized it would have to be satisfactory to customers. Option 4 would require a drastic change in perspective that Option 3 would not: a switch to thinking of clothing not as a long-term investment but as a commodity to be purchased regularly, as is food. Indeed, many business people practice something close to this approach, since they take suits, shirts, blouses, and other garments to the dry cleaners once or twice a week. For them, at least, it would not be a great leap to stop at the clothing store rather than the dry cleaners. An additional advantage is that wardrobe changes would be quick and convenient – one could change clothing styles every week as easy as not.

5 Discussion

This brief study has not encompassed several items that a complete study would treat. For example, our present washers and dryers were designed for cotton fabrics and blends, yet cotton growing is known to require large amounts of water and pesticides, and thus to be a heavy load on the environment [11]. Polyester and other fibers are substantially better on that score and might fit neatly into an alternative cleaning or one-time system.

RLCA is not a tool that necessarily gives a ready answer to the question of which option is best from an environmental standpoint. In the example here, **Option 1** involves significant energy and water use and disposal. **Option 2** is similar, but utilizes or produces less of each. **Option 3** involves a new cleaning technology with uncertain physical and financial properties, and **Option 4** trades off energy and water use on customer premises for additional manufacturing and product transport, with their attendent environmental impacts.

In addition, a societal transformation is required for Option 4, and such transformations are typically difficult to achieve. Perhaps equally significant is the realization that time and investment are required for technological change, particularly those changes implied by Options 3 and 4, so the anticipated technological transition period must be part of the decision perspective.

However, the present purpose is not necessarily to select the best alternative for the provisioning of clean clothing, but to study the utility of the RLCA itself. Two interesting characteristics arise naturally out of performing a reverse life-cycle assessment. The first is that RLCA leads the designer into moving her or his thinking out of its traditional paths and into potentially more innovative ones. In all likelihood, some of these paths will be feasible and some not, a finding that may inspire research efforts to achieve feasibility for an approach that looks promising but is currently intractable. The second characteristic is that RLCA leads the designer into systems thinking, of trying to assess what approach to a societal need is most apposite from an overall perspective, rather than from the perspective of a small niche. RLCA is thus particularly appropriate for long-range corporate or governmental planning.

Because of the technological and societal complexities of alternative ways of meeting a need, the best choice for meeting that need is seldom obvious, and detailed study and consensus-building will generally be required. The real benefit of the RLCA is not necessarily that it readily produces the right choice among options, but that it forces broad, innovative, systems thinking rather than attempting to achieve incremental improvements on an existing system without exploration of additional possibilities. The RLCA will not always be a tool that provides great new insights, but it has that potential, and should thus be a part of the arsenal of every industrial ecologist.

Acknowledgement

S.D. Noesen of the Dow Chemical Company had the initial inspiration of performing a reverse LCA/SLCA. That inspiration, and his comments, those of B.R. Allenby, and of two anonymous referees on an earlier version of this paper, are gratefully acknowledged.

6 References

[1] Curran, M.A.: Broad-Based Environmental Life Cycle Assessment, Environmental Science and Technology 27, 430–436 (1993)
[2] Weitz, K.A.; Malkin, M.; Baskir, J.N.: Streamlining Life-Cycle Assessment: Conference and Workshop Summary Report, Research Triangle Park, NC: Research Triangle Institute (1995)
[3] Owens, J.W.: Discussion Paper on the Feasibility of Developing Characterization Models for Various Impact Categories, ISO/TC 207/SC 5/WG 4/N 30, International Standards Organization, Stockholm (1995)
[4] Wheeler, D.: What Future for Product Lifecycle Assessment? Integrated Environmental Management 20, 15–19 (1993)
[5] Dixcee, A.: Washing machine design: The environmental dimension, Industry and Environment, Oct.-Dec. 1993, pp. 43–45, Nairobi: United Nations Environment Programme
[6] Graedel, T.E.; Allenby, B.R.; Comrie, P.R.: Matrix Approaches to Abridged Life-Cycle Assessment, Environmental Science and Technology 29, 134A-139A (1995)
[7] Graedel, T.E.; Allenby, B.R: Industrial Ecology, Englewood Cliffs, N.J.: Prentice-Hall (1995)
[8] Graedel, T.E.: Weighting Functions in Streamlined Life-Cycle Assessment, Intl. J. Life Cycle Assessment 1, 85–89 (1996)
[9] ISO/DIS 11469, Generic Identification and Marking of Plastic Parts; ISO 1043, Plastics – Symbols, Parts 1–3; SAE J1344, Marking of Plastic Parts
[10] American Fiber Manufacturers Association, Resource and Environmental Profile Analysis of a Manufactured Apparel Product: Woman's Knit Polyester Blouse, Washington, D.C. (1993)
[11] Brown, L.R.; Flavin, C.; Kane, H.: Vital Signs, 1996, New York: W.W. Norton (1996)